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(54) Method and apparatus for detecting stator faults in rotary dynamoelectric machines

Verfahren und Anordnung zum Feststellen von Statorfehlern in rotierenden dynamoelektrischen Maschinen

Procédé et dispositif de détection de défaillances du stator dans des machines dynamo-électriques tournantes

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Description

[0001] This invention relates to a method of detecting and locating stator faults in dynamoelectric machines during operation thereof, and to an apparatus for implementing the method. Specifically, the invention is concerned with the detection and location of a shorted turn of the stator winding by monitoring the axial leakage flux.

[0002] Studies on reliability and failure mechanisms of dynamoelectric machines with multiturn stator coils indicate that stator insulation breakdown is one of the major causes of failure. Additionally there is evidence that the majority of stator winding failures in such machines result from turn insulation breakdown. In some cases where there has been minimal or no core damage due to the fault, it is possible to isolate the damaged coil from the rest of the winding and restart the machine. Such an operation may necessitate isolation of other coils in order to retain balanced operation of the machine. In this way the machine can be returned to service quickly, albeit with degraded performance until a more complete repair or winding replacement can be scheduled. Unfortunately location of the failed coil is difficult and time consuming.

[0003] IEEE Proc. B. El. Power Appl., Vol. 133, no. 3, pages 142 to 148 discloses a method of monitoring electric drives in order to pre-empt occurrences of failures and to give an early indication of the onset of possible failures. Fault signatures are used to identify the type of fault which may occur and to give an early indication of the onset of a possible malfunction. Specifically, a possible malfunction is detected by measuring the harmonic components in axial leakage flux and comparing the measured harmonics with known fault signatures.

[0004] The object of the present invention is to provide a method of, and a device for, detecting the occurrence of a shorted turn and indicating its location in the stator winding of the machine while the machine is still running.

[0005] According to a first aspect of the present invention, there is provided a method of detecting and locating stator faults in a dynamoelectric machine having a rotor and a stator with multiturn stator coils by monitoring changes in axial leakage flux during operation of the machine, comprising:

identifying the frequencies of selected harmonic components of axial leakage flux that are to be significantly affected by the occurrence of a stator fault,
detecting the axial leakage flux at each of at least four positions, including a datum position, distributed symmetrically around the axis of the rotor adjacent to an end winding of the stator,
deriving from the detected flux at each of said positions a first signal having a value corresponding to the magnitude of the detected flux,
storing the values of said first signals derived prior to the occurrence of a stator fault,
deriving from the detected axial leakage flux a further signal having a value corresponding to the magnitude of said selected harmonic components,
monitoring said further signal and detecting a change therein thereby detecting the occurrence of a stator fault,
storing the values of said first signals derived after the occurrence of the stator fault, and
comparing the values of said first signals stored before and after the occurrence of a stator fault and storing the differences therebetween,

characterized in that the method further comprises:

determining from said comparison a value representing the angular position of the stator fault with respect to the datum position by:

(i) storing a value R_1 representing the radial distance of said four positions from the axis of the stator,
(ii) storing a value R_2 representing the mean radius of the stator end winding,
(iii) computing values B_1 and B_2 corresponding respectively to the moduli of said differences between the stored values of said first signals derived from the detected flux at one diametrically opposed pair of said flux detecting positions,
(iv) computing values B_3 and B_4 corresponding respectively to the moduli of said differences between the stored values of said first signals derived from the detected flux at the other diametrically opposed pair of said flux detecting positions,
(v) computing values ψ_1 and ψ_2, where

$$\pm \psi_1 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\bullet(B_1-B_2)/(B_1+B_2)]$$

$$\pm \psi_2 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\bullet(B_3-B_4)/(B_3+B_4)],$$

(vi) determining therefrom the angular position of the stator fault ψ_o with respect to said datum position from the relationship

$$\psi_o = \psi_1 = \psi_2 + 90°$$

and (vii) displaying the value ψ_o.

[0006] The occurrence of a stator fault representing a shorted turn is thus detected by monitoring selected axial flux harmonics which are sensitive to the occurrence. The angular position of the fault is computed from stored values, namely machine parameters which are initially known and measured values of the flux after detection of the fault.

[0007] According to a second aspect of the present invention, there is provided an apparatus for detecting and locating stator faults in an induction motor by monitoring changes in axial leakage flux during operation of the motor, comprising:

means for detecting the axial leakage flux during operation of the motor, said means including means for deriving a plurality of first signals each having a value corresponding to the detected flux at a respective one of at least four positions, including a datum position, distributed around the axis of the motor,
means for deriving from the detected flux a further signal corresponding to the magnitude of the detected flux at selected harmonic frequencies,
first data processing means for monitoring said further signal and for detecting the occurrence of a stator fault by a change in the value thereof, and
second data processing means responsive to said first data processing means, said second data processing means including:

(a) means for storing said first signals prior to the occurrence of a stator fault, and
(b) means responsive to the detection of a stator fault for storing said first signals after the occurrence of the fault,

characterized in that said second data processing means further includes:

(c) means for computing from said stored values of said first signals the angular position of the stator fault with respect to said datum position,
(d) said means for computing including:

(d1) means for storing a value R_1 representing the radial distance of said four positions from the axis of the stator,
(d2) means for storing a value R_2 representing the mean radius of the stator end winding,
(d3) means for computing values B_1 and B_2 corresponding respectively to the moduli of said differences between the stored values of said first signals derived from the detected flux at one diametrically opposed pair of said flux detecting positions,
(d4) means for computing values B_3 and B_4 corresponding respectively to the moduli of said differences between the stored values of said first signals derived from the detected flux at the other diametrically opposed pair of said flux detecting positions,
(d5) means for computing values ψ_1 and ψ_2, where

$$\pm \psi_1 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\bullet(B_1-B_2)/(B_1+B_2)]$$

$$\pm \psi_2 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\bullet(B_3-B_4)/(B_3+B_4)],$$

(d6) means for determining therefrom the angular position of the stator fault ψ_o with respect to said datum position from the relationship

$$\pm \psi_o = \psi_1 = \psi_2 + 90°$$

and (d7) displaying the value ψ_o.

[0008] The preferred method according to the invention, and an apparatus therefor, will now be described by way of example with reference to the accompanying drawings. In the drawings:

Figure 1 is a graph showing the waveform of detected magnetomotive force (MMF) due to a shorted stator turn;

Figures 2 and 3 are diagrams illustrating the geometric considerations required in magnetic field calculation;

Figure 4 is a diagram illustrating the geometry of sensors used to detect axial leakage flux;

Figure 5 is a partially diagrammatic illustration of an apparatus used to monitor axial leakage flux;

Figure 6 is a diagram illustrating the general algorithm used to detect and locate a stator fault; and

Figure 7 is a diagram illustrating the detailed algorithm used to locate the stator fault.

Basic Principles

[0009] In the case of an ideal electrical machine there is zero net axial magnetic leakage flux because the stator and rotor currents should exactly cancel one another. However, in practice, due to nonuniformities in materials and construction methods, such a situation does not occur. Hence associated with all rotating machines there is a small, but measurable, axial leakage flux. This magnetic flux can be measured by the simple expedient of placing a search coil, or other appropriate magnetic flux sensing device, in close proximity to the end region of the machine. The output from such a device, when analyzed in the frequency domain, is manifest as a series of harmonics of varying magnitude. From basic electromagnetic considerations of electrical machines it is possible to derive expressions which permit the harmonic components inherent in the axial leakage flux to be predicted. The equations, which are simple algebraic expressions, only require knowledge of the number of poles and rotational speed of the machine, in order to calculate all possible harmonics for a particular machine.

[0010] The occurrence of a stator fault in an induction motor, for example, will inevitably result in a change in the air gap space harmonic distribution. These space harmonics cannot be detected directly by a search coil. However, the search coil can detect the time harmonics of the axial flux. Thus it is necessary to derive the relationship between the space and time harmonics in order to correctly interpret the frequency spectrum obtained from the search coil. For the purpose of this work, considering only the supply fundamental and the third harmonic component due to saturation, the space harmonic distribution of MMF due to a balanced, full pitched, three phase winding fed from a balanced supply frequency, ω, is given by [1],

$$m = 0.955N_1[k_{w1}\cos(\omega t-p\theta)+0.2k_{w5}\cos(\omega t+5p\theta)$$

$$-0.14k_{w7}\cos(\omega t-7p\theta)+0.09k_{w11}\cos(\omega t+11p\theta)-...] \quad (1)$$

where

k_{wn} is the n^{th} winding factor
p is the number of pole pairs
θ is the angular displacement from the stator datum

[0011] This represents a rotating set of harmonics of order $6n\pm1$ which can be simplified to the corresponding air gap fluxes,

$$B_s = B_1\cos(\omega t-p\theta)+B_5\cos(\omega t+5p\theta)-B_7\cos(\omega t-7p\theta)$$

$$+B_{11}\cos(\omega t+11p\theta) \quad (2)$$

where B_n are the spatial harmonic fluxes.

[0012] This expression is in the stator frame of reference. Consequently, because the shaft flux of the rotor is of interest, it is necessary to refer equation (2) to the rotor reference frame. Consider the situation in which β is the angular displacement between the rotor and stator datum positions, and a is defined to be the angular displacement from the rotor datum. Then $\theta = \alpha + \beta$.

[0013] If the angular rotor speed is ω_r, then,

$$\theta = \alpha+\omega_r t \tag{3}$$

now using the normal expression for the slip of the motor, i.e. $s = (\omega_s-\omega_r)/\omega_s$, where ω_s, the synchronous speed, $= \omega/p$,

$$\omega_r = \omega(1-s)/p \tag{4}$$

[0014] Now, the general term of equation (2) is,

$$B_{ns} = B_n\cos(\omega t\pm np\theta) \tag{5}$$

substituting equations (3) and (4) into (5) leads to,

$$B_{ns} = B_n\cos[(1\pm n(1-s))\omega t\pm np\alpha] \tag{6}$$

[0015] Expanding the expression for the first few terms gives,

$$B_s = B_1\cos(s\omega t-p\alpha)+B_5\cos[(6-5s)\omega t+5p\alpha]$$
$$-B_7\cos[7s-6)\omega t-7p\alpha]+B_{11}\cos[(12-11s)$$
$$+ 11\, p\alpha]- \tag{7}$$

[0016] Equation (7) gives the frequency components of the currents that are induced in the rotor due to the air gap space harmonics of a balanced winding and supply. In addition to these harmonics, the fundamental of the supply frequency will also appear in the axial flux spectrum. The presence of additional, higher order, harmonics can be accounted for by using the term $n\omega$ rather than ω.

[0017] Having derived the harmonic components of axial flux due to asymmetries in a "healthy" machine, the situation in which an interturn short circuit is introduced is now considered. The effect of the interturn fault is to remove a turn from the stator winding. This will have a small, but finite, effect on the main air gap flux distribution. In addition, an emf will be induced in the shorted turn which will result in a current flow limited only by the self impedance of the fault. This impedance essentially determines the transition time between turn and groundwall insulation failure.

[0018] The fault current due to the shorted turn is the source of an additional MMF pulse. This MMF pulse also has a space harmonic distribution which is superposed on the main field distribution. From previous considerations, this will lead to a change in the time harmonics observed in the leakage field. The changes to be expected can also be predicted mathematically, as follows:

[0019] Simple consideration of the MMF distribution due to an interturn short circuit leads to the characteristic illustrated in Figure 1. This is the case for a four pole machine. The analysis to be outlined below is for the general case of a 2p pole machine.

[0020] Fourier analysis of the MMF waveform, illustrated in Figure 1, shows that it contains all harmonics except the fourths, i.e.,

$$B_s = 0.5\Sigma B_n\cos(\omega t\pm n\theta), n \neq 4m, \text{ all } m \tag{8}$$

[0021] For the general case, the corresponding waveform would have a mark-space ratio of 1:(2p-1) causing every

$2p^{th}$ harmonic to be absent. Hence the time harmonics produced by the rotor are given by,

$$B_s = 0.5\Sigma B_n \cos[(1 \pm n(1-s)/p)\omega t \pm n\alpha],\ n \neq 2pm, \quad (9)$$

[0022] Adding in supply time harmonics of higher order k, leads to the completely general expression,

$$B_s = 0.5\Sigma\Sigma B_n \cos[(k \pm n(1-s)/p)\omega t \pm n\alpha],\ n \neq 2pm, \quad (10)$$

[0023] Although this is a large series, only the lower order harmonics are significant. The key element of this expression is,

$$[k \pm n(1-s)/p]f_1$$

$$\text{for } k = 1,3 \text{ and } n = 1,2,3,\ldots\ldots\ldots,(2p-1) \quad (11)$$

[0024] The $n\alpha$ term in the argument of (10) causes the components defined above to beat at the slip frequency of the rotor current.

[0025] Thus the following procedure can be employed to identify the stator fault:

1. Calculate air gap space harmonics due to balanced supply and winding conditions.

2. Derive associated time harmonic currents (fluxes) in rotor and stator reference frames.

3. Refer all time harmonic components to the stator frame, since the search coil is stationary. These are the components to be expected in the "healthy" machine.

4. Calculate additional space harmonics injected by the occurrence of an interturn short circuit.

5. Relate these to additional time harmonics in the spectrum of the axial field.

6. Look for changes in these components, which can be predicted for a given machine, to indicate the presence of an interturn fault.

[0026] Having determined that a stator fault condition exists, the next task is to locate the position of the fault within the stator winding. The introduction of a shorted turn in the stator winding produces an asymmetry in the magnetic field in the endwinding of the machine. This is because the short circuit current flowing in the fault is not balanced by an equal current flowing in the corresponding phase belt which is situated diametrically opposite the faulted turn. Thus, by measuring the asymmetry in the endwinding magnetic field the position of the faulted coil within the stator winding can be determined.

[0027] The technique relies upon the use of an array of at least four search coils, or other appropriate sensors, distributed axisymmetrically about the drive shaft of the motor. These coils provide a local measure of the magnetic field in the end region of the machine. By triangulating the outputs from the search coils, it is possible to determine the location of the stator coil containing the interturn short circuit. In order to accomplish this function it is necessary to develop an expression for the field at any point on the circumference of the circle passing through the centres of the search coils due to the current flowing in the end winding of an arbitrarily positioned turn of the stator winding. By invoking the Biot-Savart law and with reference to Figure 2, one can deduce

$$d\underline{B} = (\mu_o\, I d\underline{l} x \underline{a}_z)/4\pi r^2 \quad (12)$$

where

$\underline{B}$ is the magnetic field strength vector
μ_o is the permeability of free space

$\underline{a}_z$ is the unit vector in the z direction

[0028] From Figure 2, and rewriting equation (12)

$$dB = (\mu_o I dl \sin\phi)/4\pi r^2 \tag{13}$$

but since $dl\sin\phi = rd\theta$,

$$dB = (\mu_o I d\theta)/4\pi r \tag{14}$$

[0029] Figure 3 illustrates the general case in which the shorted turn is displaced an angular amount ψ, from an arbitrary datum position. In this case R_2 is the mean radius of the end winding, and R_1 is the radius of the circle on which the field is to be calculated. The circles are assumed to be coplanar and concentric. The length of arc of the coil is L and the field measurement point is displaced an angle δ from the datum. Using the cosine rule,

$$r^2 = R_1^{\ 2}+R_2^{\ 2}-2R_1R_2\cos(\psi+\delta) \tag{15}$$

[0030] If R_2 is very much greater than R_1, then $L \approx r\theta$, thus

$$\theta = L/[R_1^{\ 2}+R_2^{\ 2}-2R_1R_2\cos(\psi+\delta)]^{0.5} \tag{16}$$

[0031] From equations (14) and (16), the value of B at the field point is given by,

$$B = \mu_o IL/[4\pi(R_1^{\ 2}+R_2^{\ 2}-2R_1R_2\cos(\psi+\delta))] \tag{17}$$

[0032] By fixing the position of a number of coils with respect to the datum, and arbitrarily assigning a reference coil at $\delta = 0$, the value of B at each coil can be found as a function of ψ. From the measured values of B, ψ can be found and consequently the position of the faulted turn.

[0033] In order to optimize the detection scheme, it is necessary to determine the minimum number of coils required for simple and reliable fault location. Consider the situation in which two coils are spaced 180° apart. Each coil will have an induced emf, proportional to the flux linking it. With reference to Figure 4, and taking the coil at position 1 to be the datum, from equation (17),

$$B_1 = k/(a-b\cos\psi) \tag{18}$$

and

$$B_2 = k/(a-b\cos(\psi+180°)) \tag{19}$$

thus

$$B_2 = k/(a+b\cos\psi) \tag{20}$$

where

$$k = \mu_o IL/4\pi$$

$$a = (R_1^{\ 2}+R_2^{\ 2})$$

$$b = 2R_1R_2$$

[0034] From equations (18) and (20), and some rearrangement of the terms,

$$\cos\psi = [a(B_1-B_2)]/[b(B_1+B_2)] \qquad (21)$$

[0035] This expressions locates the fault to within $\pm\psi$ because,

$$\pm\psi = \cos^{-1}[\ 0.5(R_1/R_2+R_2/R_1)\{(B_1-B_2)/(B_1+B_2)\}] \qquad (22)$$

[0036] In practice the measured values of the emf induced in the coils can be used because the B values are ratioed in equation (22).

[0037] Consequently the values used when attempting fault location should be the modulus of the difference between the "healthy" and "faulted" conditions. In order to locate uniquely the fault, a second set of coils, 3 and 4, is required, as shown in Figure 4. For convenience they are displaced at right angles to the axis of symmetry of coils 1 and 2. However, the angular displacement of the coils is not critical. Repeating the location procedure in the same fashion as above with the second set of coils, will yield $\pm\psi_{p2}$, which differentiates it from $\pm\psi_{p1}$, found from coils 1 and 2. If the higher magnitude coil signal is chosen as the point from which to measure, then ψ will always fall within the range of 0° to 90°. In addition, only one quadrant will contain an angular position identified using both sets of coils. This is the approximate location of the fault.

[0038] In order to clarify the procedure for locating the position of a faulted coil within the stator winding, reference should be made to Figure 4. For the purpose of the location algorithm, the coils are grouped in pairs. In this case coils 1 and 2 form one pair, and coils 3 and 4 form the other pair.

[0039] Initially, at a point in time at which the motor is considered to be healthy, the induced emf value on each of the coils is measured and recorded. In the event of an interturn short circuit occurring, the emf values on each of the coils are again recorded. These latter values are subtracted from the initial values and the modulus of the resultant is taken. Subsequently, the four positive numbers thus derived, i.e. B_1, B_2, B_3 and B_4, are input into the fault location algorithm. This operation results in two expressions,

$$\pm\ \psi_{p1} = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)((B_1-B_2)/(B_1+B_2))]$$

and,

$$\pm\psi_{p2} = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)((B_3-B_4)/(B_3+B_4))]$$

[0040] The resultants from these expressions are angles. The reference points are taken as the coils, in each pair, upon which the largest emf value was recorded. Thus, if for example coil 1 had the largest reading between coils 1 and 2, one would say that the position of the fault was $\pm\psi p_1$ from coil 1. Similarly, if the reading on coil 4 was the larger of the readings on coils 3 and 4, the fault would be located $\pm\psi_{p2}$ from coil 4. Hence, it is a simple step to draw the conclusion that, in this case, the the fault must lie in the quadrant between coils 1 and 4 at the angular position ψ_{p1}-ψ_{p2}/2.

[0041] To summarize,the detection and location scheme is as follows:

from machine parameters calculate the axial leakage flux components under normal conditions,

calculate which of the harmonics will change as the result of an interturn short circuit search for these components in the axial leakage field of the machine, and

upon fault indication apply the fault location technique described above.

Implementation of the Method

[0042] Figure 5 illustrates a preferred apparatus used to detect and locate the occurrence of a shorted turn of the stator winding 11 of an induction motor 10 by monitoring changes in the axial leakage flux during operation of the motor. The apparatus comprises two subsystems, namely means for sensing the axial leakage flux and means for processing the signals derived therefrom. A further subsystem, which may be necessary in some cases, is some form of speed measurement in order to gain a measure of the slip of the motor when loaded.

[0043] The flux sensors shown in Figure 5 are air cored coils 13, which are inexpensive and easily fabricated. The preferred location of the search coils is axisymmetric with the drive shaft of the motor, either inside or outside the motor casing. In the illustrated embodiment there are four search coils 13 distributed symmetrically around the axis of the motor adjacent to an end winding of the stator 11. In principle there could be more than four search coils, but the use of four search coils arranged as diametrically opposed pairs simplifies the signal processing procedures and circuitry.

[0044] Speed measurement, if required, can be accomplished in a number of ways. In some cases, speed information is available at the motor control centre in the plant. However, it is possible that some type of transduction system may be necessary. A measure of the rotational speed of the rotor is needed in order to calculate the slip of the motor. The slip is required because the harmonics of the axial leakage flux are dependent on the slip of the motor. Rotational speed can easily be obtained by measuring the time required for a reference point on the drive shaft to complete one revolution. In practice this can be done by painting a stripe on the drive shaft and using a device such as a photo transistor to generate an electrical pulse each time the stripe passes under the photo transistor.

[0045] It is necessary to condition the voltage signals derived from the search coils, which are normally of only a few millivolts. In order to bring these signals to more manageable levels they are amplified by preamplifiers 14. Furthermore, in order to remove the power frequency component, which is relatively high and likely to saturate subsequent amplifier stages, the signals are filtered by power frequency notch filters 15. Alternatively, very wide dynamic range amplifiers may be used. The four analogue signals, after conditioning, are digitized to produce respective "first" signals having magnitudes corresponding to the harmonic flux detected by the four search coils 13. These "first" signals are subsequently processed by a computer 16 as hereinafter described, to determine the angular position of a detected stator fault.

[0046] The analogue signals from the notch filters 15 are also summed by a summing amplifier 17, the summed signal then being digitized. This summed signal must now be decomposed into its harmonic components. Two practical approaches to this task are possible. Given that the components of the axial leakage flux are mathematically predictable, a set of filters, tuned to the frequencies of interest, can be used. The outputs of these filters can be monitored for changes which potentially indicate the onset of a fault condition. In practice, in view of the variety of motor designs which exist, construction of discrete filters tailored to the motor parameters is not a practical approach. However, by using digitally controlled analogue filters, it is possible to set up an array of filters which can be readily customized to the particular motor. For example, a single controllable filter may be sequentially stepped through the predetermined frequencies of interest.

[0047] The preferred method, according to the present invention, of decomposing the signal into its harmonic components is to digitize the signal from the summing amplifier 17 and to transform the digital signal to the frequency domain by means of a fast Fourier transform (FFT). In this way, a further signal having a value corresponding to the magnitude of selected harmonic components of axial leakage flux is derived. The harmonic components are selected as being those which are significantly affected by the occurrence of a stator fault.

[0048] The preferred method will now be described with reference to Figures 6 and 7.

[0049] In order to detect the occurrence of a stator fault by monitoring changes in the axial leakage flux, it is first necessary to identify the frequencies of the harmonic components which are significantly affected by the occurrence. These can be calculated from the machine parameters and the conditions under which the motor is operating.

[0050] Referring to Figure 6, the first thing to do is to input into the computer the relevant input parameters, specifically the number of poles of the motor and its nominal speed (BLOCK 21). From these parameters the harmonic components of axial leakage flux under faulted and no-fault conditions are computed (BLOCK 22). If the motor is on-load (BLOCK 23), the rotor velocity has to be taken into account (BLOCK 24); in either case the results of the calculation are input into the initialization procedure (BLOCK 25). The summed outputs from the search coils are recorded at a first period t(n) and converted to the frequency domain, → A(f,t(n)) (BLOCK 26) as previously described. The results are tested (BLOCK 27) and should confirm the calculations of (BLOCK 23).

[0051] The next step in the procedure is to measure and record the summed output of induced emf on each of the search coils at a second period t(n+1), and converted to the frequency domain, → A(f,t(n+1)) (BLOCK 29).L If a possible fault is detected by applying the test

$$A(f,t(n+1)) >> A(f,t(n)) \qquad \text{(BLOCK 30)}$$

then the summed output from the search coils is measured and recorded at a third period and converted to the frequency domain, →A(f,t(n + 2)) (BLOCK 31). The possible fault is confirmed or ignored by testing whether

$$A(f,t(n+2)) \gg A(f,t(n)) \qquad \text{(BLOCK 32)}$$

[0052] If the result is positive, the fault is confirmed; otherwise it can be taken that the apparent fault was due to a temporary or spurious event.

[0053] If the fault is confirmed, the rms value of induced emf in each of the search coils in the faulted condition of the motor is measured and recorded, (BLOCK 33). The emf value for the faulted condition is subtracted from the stored emf value for the healthy condition, for each search coil, and the modulus of the difference is taken (BLOCK 34). From the moduli value so obtained the angular position of the fault with respect to a datum position can be calculated, (BLOCK 35), as will be described with reference to Figure 7. The occurrence of the stator fault, and its position in the stator winding, are then displayed (BLOCK 36).

[0054] Upon confirmation of the occurrence of a stator fault (BLOCK 32), the angular position of the fault is determined by using the algorithm illustrated in Figure 7. This algorithm involves the use of values derived from signals obtained after the occurrence of the fault, as will now be described, as well as the following values:

R_1 =	radius of the circle on which the axes of the search coils lie, this value having been entered and stored initially;
R_2 =	mean radius of the end winding of the stator, this value having been entered and stored initially;
EMF (healthy) =	the values of said "first" signals derived from the search coils, these values having been stored prior to the occurrence of the fault.

[0055] Referring to Figure 7, the number of search coils n was previously entered into the computer and stored (BLOCK 41). In the present example n = 4, and in the algorithm the individual search coils are identified by the letter x, where x = 1, x = 2, x = 3 and x = 4, respectively.

[0056] The signals from the search coils, previously referred to as the "first" signals, are examined in turn, (BLOCKS 42, 43, 44). The "first" signal from each of the search coils corresponds to the axial leakage flux detected by the search coil, being derived from the voltage signal which is a measure of the rms value of the emf induced in the coil. The value of this signal, denoted by EMF (faulted, position x), is subtracted from the previously stored value of the signal EMF (healthy, position x), (BLOCK 45), and the modulus |B(x)| is taken (BLOCK 46).

[0057] The computer now has in store all the necessary values and parameters from which the angular position of the stator fault can be computed, namely R_1, R_2, B_1, B_2, B_3, B_4. From these values the following relationships are derived, (see BLOCK 47):

$$\pm\,\psi_1 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\bullet(B_1-B_2)/(B_1+B_2)]$$

$$\pm\,\psi_2 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\bullet(B_3-B_4)/(B_3+B_4)]$$

Since $\psi = \psi_2 + 90°$, the required angular position of the fault ψ_0 can be determined. In other words the quadrant in which the fault lies can be readily determined.

[0058] Thus, considering the first pair of diametrically opposed search coils 1, 2, one must determine whether EMF (fault, 1) is greater or less than EMF(fault, 2), (BLOCK 48). If it is greater, then the fault is at one of the positions $\pm\psi_1$ from coil 1,(BLOCK 49). If it is less, then the fault is at one of the positions $\pm\psi_1$ from coil 2, (BLOCK 50). In order to resolve the ambiguity, one must now determine whether EMF(fault, 3) is greater or less than EMF(fault, 4), (BLOCK 51). If it is greater, then the fault is at a position $\pm\psi_2$ from coil 3, (BLOCK 52), while if it is less the fault is at one of the positions $\pm\psi_2$ from coil 4, (BLOCK 53). The fault obviously lies within the quadrant defined by $\pm\psi_1$ and $\pm\psi_2$, (BLOCK 54); that is to say, the angular position ψ_0 of the fault with respect to the datum position is given by

$$\psi_o = \psi_1 = \psi_2 + 90°.$$

This position is displayed along with indication that a fault has occurred.

Claims

1. A method of detecting and locating stator faults in a dynamoelectric machine having a rotor and a stator with multiturn stator coils by monitoring changes in axial leakage flux during operation of the machine, comprising:

   identifying the frequencies of selected harmonic components of axial leakage flux that are to be significantly affected by the occurrence of a stator fault,
   detecting the axial leakage flux at each of at least four positions, including a datum position, distributed symmetrically around the axis of the rotor adjacent to an end winding of the stator,
   deriving from the detected flux at each of said positions a first signal having a value corresponding to the magnitude of the detected flux,
   storing the values of said first signals derived prior to the occurrence of a stator fault,
   deriving from the detected axial leakage flux a further signal having a value corresponding to the magnitude of said selected harmonic components,
   monitoring said further signal and detecting a change therein thereby detecting the occurrence of a stator fault,
   storing the values of said first signals derived after the occurrence of the stator fault, and
   comparing the values of said first signals stored before and after the occurrence of a stator fault and storing the differences therebetween,

   characterized in that the method further comprises:

   determining from said comparison a value representing the angular position of the stator fault with respect to the datum position by:

   (i) storing a value R_1 representing the radial distance of said four positions from the axis of the stator,
   (ii) storing a value R_2 representing the mean radius of the stator end winding,
   (iii) computing values B_1 and B_2 corresponding respectively to the moduli of said differences between the stored values of said first signals derived from the detected flux at one diametrically opposed pair of said flux detecting positions,
   (iv) computing values B_3 and B_4 corresponding respectively to the moduli of said differences between the stored values of said first signals derived from the detected flux at the other diametrically opposed pair of said flux detecting positions,
   (v) computing values ψ_1 and ψ_2, where

$$\pm \psi_1 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\cdot(B_1-B_2)/(B_1+B_2)]$$

$$\pm \psi_2 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\cdot(B_3-B_4)/(B_3+B_4)],$$

   (vi) determining therefrom the angular position of the stator fault ψ_o with respect to said datum position from the relationship

$$\psi_o = \psi_1 = \psi_2 + 90°$$

   and (vii) displaying the value ψ_o.

2. A method according to claim 1, wherein the storage of said first signals derived after the occurrence of a stator fault is initiated by the detection of the fault.

3. A method according to claim 1 or 2, wherein the axial leakage flux is detected at each of four positions, including said datum position, distributed symmetrically around said axis.

4. A method according to any one of claims 1 to 3, wherein the spectrum of axial leakage flux is analysed by deriving a respective voltage signal corresponding to the detected leakage flux at each of said plurality of positions, summing the derived voltage signals, digitising the sum of said voltage signals, and transforming the digitised signal to the frequency domain by means of a fast Fourier transform.

5. Apparatus for detecting and locating stator faults in an induction motor (10) by monitoring changes in axial leakage flux during operation of the motor, comprising:

means (13) for detecting the axial leakage flux during operation of the motor, said means including means for deriving a plurality of first signals each having a value corresponding to the detected flux at a respective one of at least four positions, including a datum position, distributed around the axis of the motor,
means for deriving from the detected flux a further signal corresponding to the magnitude of the detected flux at selected harmonic frequencies,
first data processing means (16) for monitoring said further signal and for detecting the occurrence of a stator fault by a change in the value thereof, and
second data processing means (16) responsive to said first data processing means, said second data processing means including:

(a) means for storing said first signals prior to the occurrence of a stator fault, and
(b) means responsive to the detection of a stator fault for storing said first signals after the occurrence of the fault,

characterized in that said second data processing means further includes:

(c) means for computing from said stored values of said first signals the angular position of the stator fault with respect to said datum position,
(d) said means for computing including:

(d1) means for storing a value R_1 representing the radial distance of said four positions from the axis of the stator,
(d2) means for storing a value R_2 representing the mean radius of the stator end winding,
(d3) means for computing values B_1 and B_2 corresponding respectively to the moduli of said differences between the stored values of said first signals derived from the detected flux at one diametrically opposed pair of said flux detecting positions,
(d4) means for computing values B_3 and B_4 corresponding respectively to the moduli of said differences between the stored values of said first signals derived from the detected flux at the other diametrically opposed pair of said flux detecting positions,
(d5) means for computing values ψ_1 and ψ_2, where

$$\pm \psi_1 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\bullet(B_1-B_2)/(B_1+B_2)]$$

$$\pm \psi_2 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\bullet(B_3-B_4)/(B_3+B_4)],$$

(d6) means for determining therefrom the angular position of the stator fault ψ_o with respect to said datum position from the relationship

$$\pm \psi_o = \psi_1 = \psi_2 + 90°$$

and (d7) displaying the value ψ_o.

6. Apparatus according to claim 5, wherein said means for detecting the axial leakage flux comprises four flux sensing coils (13) mounted symmetrically around the axis of the stator (11) adjacent to an end winding thereof.

Patentansprüche

1. Verfahren zum Erfassen und Lokalisieren von Statorfehlern in einer dynamoelektrischen Maschine mit einem Rotor und einem Stator, mit Statorspulen mit mehreren Wicklungen, durch Überwachen von Veränderungen des axialen Leckflusses während des Betriebes der Maschine, mit den Merkmalen:

Identifizieren der Frequenzen ausgewählter harmonischer Komponenten des axialen Leckflusses, die durch das Auftreten eines Statorfehlers in signifikanter Weise beeinflußt werden sollten,

Erfassen des axialen Leckflusses an jeder von zumindest vier Positionen, einschließlich einer Ausgangsposition, welche symmetrisch um die Achse des Rotors in der Nähe einer Entwicklung des Stators verteilt sind,

Ableiten eines ersten Signals aus dem erfaßten Fluß an jeder der Positionen, wobei das Signal einen Wert hat, welcher der Größe des erfaßten Flusses entspricht,

Speichern der Werte der ersten Signale, die vor dem Auftreten eines Statorfehlers abgeleitet wurden,

Ableiten eines weiteren Signals aus dem erfaßten axialen Leckfluß, wobei das Signal einen Wert hat, welcher der Größe der ausgewählten harmonischen Komponenten entspricht,

Überwachen des weiteren Signals und Erfassen einer Veränderung desselben, um dadurch das Auftreten eines Statorfehlers zu erfassen,

Speichern der Werte der nach dem Auftreten des Statorfehlers abgeleiteten ersten Signale, und

Vergleichen der Werte der ersten Signale, die vor und nach dem Auftreten eines Statorfehlers gespeichert wurden und Speichern der Unterschiede dazwischen,

dadurch gekennzeichnet, daß das Verfahren weiterhin aufweist:

aus dem Vergleich Bestimmen eines Wertes, welcher die Winkelposition eines Statorfehlers bezüglich der Ausgangsposition wiedergibt, durch:

(i) Speichern eines Wertes R_1, welcher den radialen Abstand der vier Positionen von der Achse des Stators wiedergibt,

(ii) Speichern eines Wertes R_2, welcher den mittleren Radius der Statorentwicklung wiedergibt,

(iii) Berechnen von Werten B_1 und B_2, die jeweils den Amplituden der Unterschiede zwischen den gespeicherten Werten der ersten Signale entsprechen, welche von dem erfaßten Fluß an einem diametral gegenüberliegenden Paar der Flußerfassungspositionen abgeleitet wurden,

(iv) Berechnen von Werten B_3 und B4, welche jeweils den Amplituden der Unterschiede zwischen den gespeicherten Werten der ersten Signale entsprechen, die von dem erfaßten Fluß an dem andern diametral gegenüberliegenden Paar von Flußerfassungspositionen abgeleitet wurden,

(v) Berechnen von Werten ψ_1 und ψ_2, wobei

$$\pm\ \psi_1 = \cos^{-1}[0{,}5(R_1/R_2+R_2/R_1)\bullet(B_1-B_2)/(B_1+B_2)]$$

$$\pm\ \psi_2 = \cos^{-1}[0{,}5(R_1/R_2+R_2/R_1)\bullet(B_3-B_4)/(B_3+B_4)]$$

(vi) daraus Bestimmen der Winkelposition des Statorfehlers ψ_o bezüglich der Ausgangsposition gemäß der Beziehung

$$\psi_0 = \psi_1 = \psi_2 + 90°$$

und (vii) Anzeigen des Wertes ψ_0.

2. Verfahren nach Anspruch 1, wobei das Speichern der ersten Signale, welche nach dem Auftreten eines Statorfehlers abgeleitet wurden, durch die Erfassung des Fehlers ausgelöst wird.

3. Verfahren nach Anspruch 1 oder 2, wobei der axiale Leckfluß an jeder der vier Positionen erfaßt wird, einschließlich der Ausgangsposition, welche symmetrisch um die Achse verteilt sind.

4. Verfahren nach einem der Ansprüche 1 bis 3, wobei das Spektrum des axialen Leckflusses analysiert wird durch Ableiten jeweils eines Spannungssignals, welches dem erfaßten Leckfluß an jeder der Mehrzahl von Positionen entspricht, Aufsummieren der abgeleiteten Spannungssignale, Digitalisieren der Summe der Spannungssignale und Transformieren des digitalisierten Signals in den Frequenzraum bzw. die Frequenzdomäne mit Hilfe einer schnellen Fourier-Transformation.

5. Vorrichtung zum Erfassen und Lokalisieren von Statorfehlern in einem Induktionsmotor (10) durch Überwachen von Veränderungen in dem axialen Leckfluß während des Betriebes des Motors, mit:

einer Einrichtung (13) zum Erfassen des axialen Leckflusses während des Motorbetriebes, wobei die Einrichtung Einrichtungen für das Ableiten einer Mehrzahl erster Signale aufweist, die jeweils einen Wert haben, welcher dem erfaßten Fluß an jeweils einer von zumindest vier Positionen entspricht, und zwar einschließlich einer Ausgangsposition, welche um die Achse des Motors verteilt sind,

Einrichtungen für das Ableiten eines weiteren Signals aus dem erfaßten Fluß, welches der Größe des erfaßten Flusses bei ausgewählten harmonischen Frequenzen entspricht,

einer ersten Datenverarbeitungseinrichtung (16) zum Überwachen des weiteren Signals und zum Erfassen des Auftretens eines Statorfehlers durch eine Veränderung in dessen Wert, und

einer zweiten Datenverarbeitungseinrichtung (16), die auf die erste Datenverarbeitungseinrichtung reagiert, wobei die zweite Datenverarbeitungseinrichtung aufweist:

(a) Einrichtungen zum Speichern der ersten Signale vor dem Auftreten eines Statorfehlers, und

(b) Einrichtungen, welche auf die Erfassung eines Statorfehlers ansprechen, um die ersten Signale nach dem Auftreten des Fehlers zu speichern,

dadurch gekennzeichnet, daß die zweite Datenverarbeitungseinrichtung weiterhin aufweist:

(c) Einrichtungen zum Berechnen der Winkelposition des Statorfehlers bezüglich der Ausgangsposition aus den gespeicherten Werten der ersten Signale,

(d) wobei die Einrichtung für das Berechnen aufweist:

(d1) Einrichtungen für das Speichern eines Wertes R_1, welcher den radialen Abstand der vier Positionen von der Achse des Stators wiedergibt,

(d2) eine Einrichtung für das Speichern eines Wertes R_2, welcher den mittleren Radius der Statorentwicklung wiedergibt,

(d3) eine Einrichtung für das Berechnen von Werten B_1 und B_2, welche jeweils den Amplituden der Unterschiede zwischen den gespeicherten Werten der ersten Signale entsprechen, die aus dem erfaßten Fluß an einem diametral gegenüberliegenden Paar der Flußerfassungspositionen erfaßt wurden,

(d4) eine Einrichtung für das Berechnen von Werten B_3 und B_4, welche jeweils den Amplituden der Unterschiede zwischen den gespeicherten Werten der ersten Signale entsprechen, die aus dem erfaßten Fluß an dem anderen diametral gegenüberliegenden Paar von Flußerfassungspositionen abgeleitet wurden,

(d5) eine Einrichtung für das Berechnen von Werten ψ_1 und ψ_2, wobei

$$\pm \psi_1 = \cos^{-1}[0{,}5(R_1/R_2+R_2/R_1)\cdot(B_1-B_2)/(B_1+B_2)]$$

$$\pm\psi_2 = \cos^{-1}[0{,}5(R_1/R_2+R_2/R_1)\bullet(B_3-B_4)/(B_3+B_4)],$$

(d6) eine Einrichtung, um daraus die Winkelposition des Statorfehlers ψ_0 bezüglich der Ausgangsposition zu bestimmen, und zwar gemäß der Beziehung

$$\pm\psi_0 = \psi_1 = \psi_2 + 90°$$

und (d7) Anzeigen des Wertes ψ_0.

6. Vorrichtung nach Anspruch 5, wobei die Einrichtung für das Erfassen des axialen Leckflusses vier Flußsensorspulen (13) aufweist, die symmetrisch um die Achse des Stators (11) in der Nähe einer Endwicklung desselben montiert sind.

Revendications

1. Procédé de détection et de localisation de défaillances du stator dans une machine dynamoélectrique, comportant un rotor et un stator à bobines statoriques multispires, par une surveillance des modifications du flux axial de fuite pendant le fonctionnement de la machine, comprenant :

   l'identification des fréquences de composantes harmoniques sélectionnées du flux axial de fuite, qui sont affectées de manière significative par l'apparition d'une défaillance du stator,
   la détection du flux axial de fuite au niveau de chacune d'au moins quatre positions, y compris une position de référence, réparties symétriquement autour de l'axe du rotor, de manière adjacente à un enroulement d'extrémité du stator,
   l'obtention, à partir du flux détecté au niveau de chacune desdites positions, d'un premier signal ayant une valeur qui correspond à la grandeur du flux détecté,
   la mémorisation des valeurs desdits premiers signaux obtenus avant l'apparition d'une défaillance du stator,
   l'obtention, à partir du flux axial de fuite détecté, d'un autre signal ayant une valeur qui correspond à l'amplitude desdites composantes harmoniques sélectionnées,
   la surveillance dudit autre signal et la détection d'une modification dans celui-ci, pour ainsi détecter l'apparition d'une défaillance du stator,
   la mémorisation des valeurs desdits premiers signaux, obtenus après l'apparition de la défaillance du stator, et la comparaison des valeurs desdits premiers signaux, mémorisés avant et après l'apparition d'une défaillance du stator, et la mémorisation des différences entre ceux-ci,

   caractérisé en ce que le procédé comprend en outre :

   la détermination, à partir de ladite comparaison, d'une valeur représentant la position angulaire de la défaillance du stator par rapport à la position de référence :

   (i) en enregistrant une valeur R_1, représentant la distance radiale desdites quatre positions par rapport à l'axe du stator,
   (ii) en enregistrant une valeur R_2, représentant le rayon moyen de l'enroulement d'extrémité du stator,
   (iii) en calculant des valeurs B_1 et B_2, correspondant respectivement aux modules desdites différences entre les valeurs mémorisées desdits premiers signaux, obtenus à partir du flux détecté au niveau d'une paire desdites positions de détection de flux, diamétralement opposées,
   (iv) en calculant des valeurs B_3 et B_4, correspondant respectivement aux modules desdites différences entre les valeurs mémorisées desdits premiers signaux, obtenus à partir du flux détecté au niveau de l'autre paire desdites positions de détection de flux, diamétralement opposées,
   (v) en calculant des valeurs ψ_1 et ψ_2, où

$$\pm\psi_1 = \cos^{-1}[0{,}5(R_1/R_2 + R_2/R_1)\ .\ (B_1 - B_2)/(B_1 + B_2)]$$

$$\pm \psi_2 = \cos^{-1} [0{,}5(R_1/R_2 + R_2/R_1) . (B_3 - B_4)/(B_3 + B_4)],$$

(vi) en déterminant, sur cette base, la position angulaire de la défaillance du stator ψ_0 par rapport à ladite position de référence, à partir de la relation

$$\psi_0 = \psi_1 = \psi_2 + 90°,$$

et
(vii) en affichant la valeur ψ_0.

2. Procédé selon la revendication 1, dans lequel la mémorisation desdits premiers signaux obtenus après l'apparition d'une défaillance du stator est lancée par la détection de la défaillance.

3. Procédé selon la revendication 1 ou 2, dans lequel le flux axial de fuite est détecté au niveau de chacune de quatre positions, y compris ladite position de référence, réparties symétriquement autour dudit axe.

4. Procédé selon l'une quelconque des revendications 1 à 3, dans lequel le spectre du flux axial de fuite est analysé par
l'obtention d'un signal de tension respectif, correspondant au flux de fuite détecté au niveau de chacune de ladite pluralité de positions, l'addition des signaux de tension obtenus, la numérisation de la somme desdits signaux de tension, et la transformation du signal numérisé en domaine fréquenciel au moyen d'une transformée de Fourier rapide.

5. Appareil de détection et de localisation de défaillances du stator dans un moteur à induction (10) par une surveillance des modifications du flux axial de fuite pendant le fonctionnement du moteur, comprenant :

un moyen (13) servant à détecter le flux axial de fuite pendant le fonctionnement du moteur, ledit moyen comportant un moyen permettant d'obtenir une pluralité de premiers signaux, ayant chacun une valeur correspondant au flux détecté au niveau de l'une d'au moins quatre positions, y compris une position de référence, réparties autour de l'axe du moteur,
un moyen permettant d'obtenir, à partir du flux détecté, un autre signal correspondant à la grandeur du flux détecté à des composantes harmoniques sélectionnées,
un premier moyen de traitement de données (16) prévu pour surveiller ledit autre signal et pour détecter l'apparition d'une défaillance du stator, par une modification de la valeur de ce signal, et
un second moyen de traitement de données (16), réagissant audit premier de moyen de traitement de données, ledit second moyen de traitement de données comprenant :

(a) un moyen pour mémoriser lesdits premiers signaux, avant l'apparition d'une défaillance du stator, et
(b) un moyen réagissant à la détection d'une défaillance du stator pour mémoriser lesdits premiers signaux après l'apparition de la défaillance,

caractérisé en ce que ledit second moyen de traitement de données comprend en outre :

(c) un moyen pour calculer, à partir desdites valeurs mémorisées desdits premiers signaux, la position angulaire de la défaillance du stator par rapport à ladite position de référence,
(d) ledit moyen prévu pour le calcul comprenant :

(d1) un moyen pour enregistrer une valeur R_1, représentant la distance radiale desdites quatre positions par rapport à l'axe du stator,
(d2) un moyen pour enregistrer une valeur R_2, représentant le rayon moyen de l'enroulement d'extrémité du stator,
(d3) un moyen pour calculer des valeurs B_1 et B_2, correspondant respectivement aux modules desdites différences entre les valeurs mémorisées desdits premiers signaux, obtenus à partir du flux détecté au niveau d'une paire desdites positions de détection de flux, diamétralement opposées,
(d4) un moyen pour calculer des valeurs B_3 et B_4, correspondant respectivement aux modules desdites différences entre les valeurs mémorisées desdits premiers signaux, obtenus à partir du flux

détecté au niveau de l'autre paire desdites positions de détection de flux, diamétralement opposées,
(d5) un moyen pour calculer des valeurs ψ_1 et ψ_2, où

$$\pm \psi_1 = \cos^{-1} [0,5(R_1/R_2 + R_2/R_1) . (B_1 - B_2)/(B_1 + B_2)]$$

$$\pm \psi_2 = \cos^{-1} [0,5(R_1/R_2 + R_2/R_1) . (B_3 - B_4)/(B_3 + B_4)],$$

(d6) un moyen permettant de déterminer, sur cette base, la position angulaire de la défaillance du stator ψ_0 par rapport à ladite position de référence, à partir de la relation

$$\pm \psi_0 = \psi_1 = \psi_2 + 90°,$$

et
(d7) l'affichage de la valeur ψ_0.

6. Appareil selon la revendication 5, dans lequel ledit moyen servant à détecter le flux axial de fuite comprend quatre bobines détectrices de flux (13) montées de manière symétrique autour de l'axe du stator (11), de manière adjacente à un enroulement d'extrémité de celui-ci.

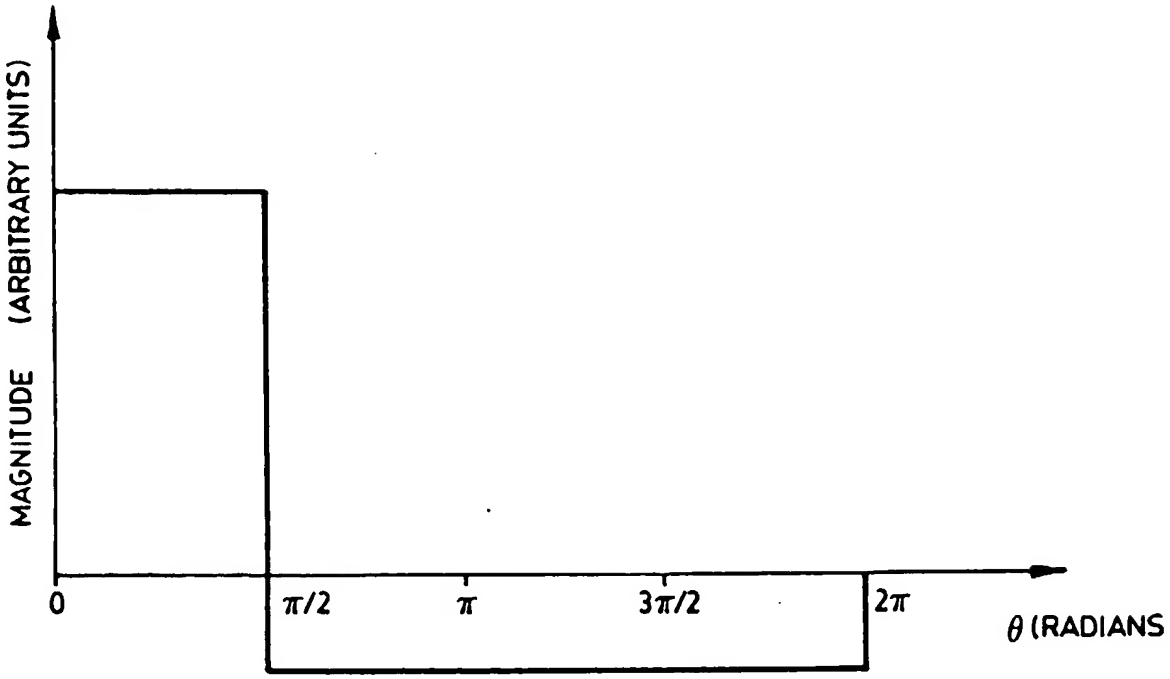


FIG. 1

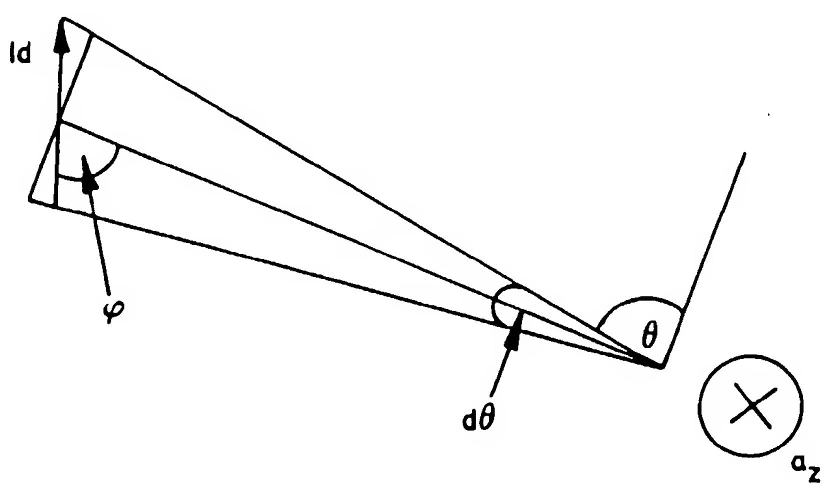


FIG. 2

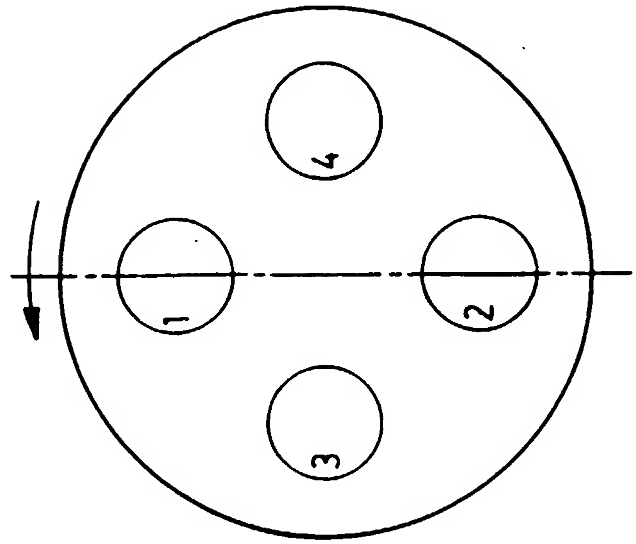


FIG. 4

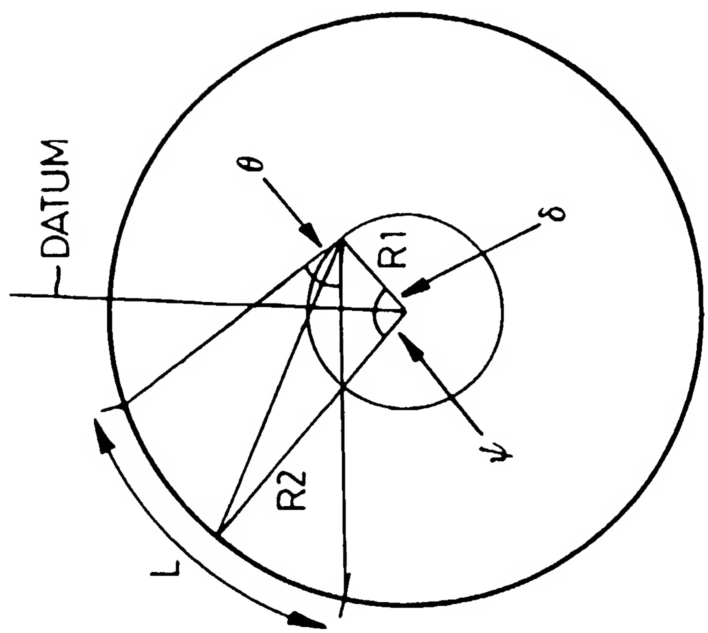


FIG. 3

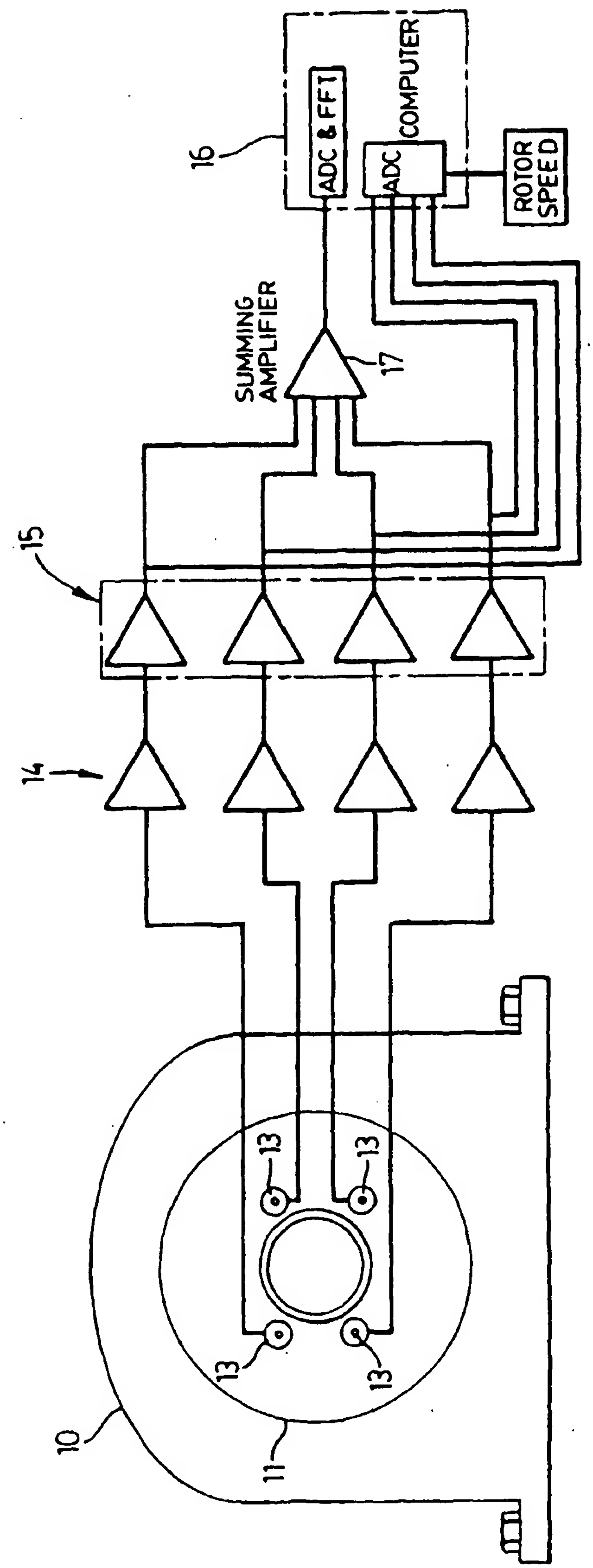
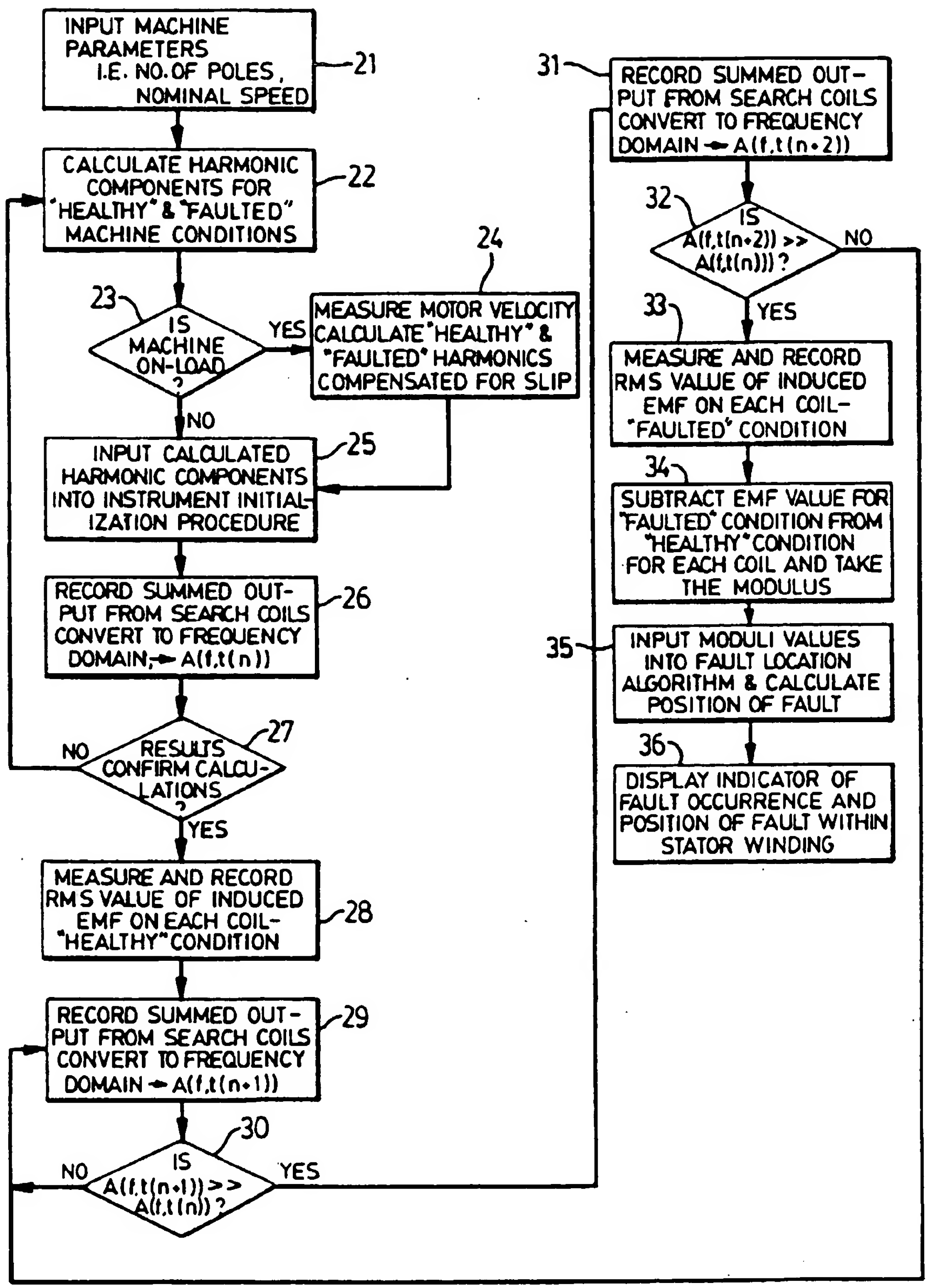

16
ADC & FFT
COMPUTER
ADC
ROTOR SPEED
SUMMING AMPLIFIER
17
15
14
13
13
13
13
10
11

FIG. 5



INPUT MACHINE PARAMETERS I.E. NO. OF POLES, NOMINAL SPEED
21
CALCULATE HARMONIC COMPONENTS FOR "HEALTHY" & "FAULTED" MACHINE CONDITIONS
22
23
IS MACHINE ON-LOAD ?
YES
NO
24
MEASURE MOTOR VELOCITY CALCULATE "HEALTHY" & "FAULTED" HARMONICS COMPENSATED FOR SLIP
25
INPUT CALCULATED HARMONIC COMPONENTS INTO INSTRUMENT INITIALIZATION PROCEDURE
26
RECORD SUMMED OUTPUT FROM SEARCH COILS CONVERT TO FREQUENCY DOMAIN → A(f,t(n))
27
RESULTS CONFIRM CALCULATIONS ?
NO
YES
28
MEASURE AND RECORD RMS VALUE OF INDUCED EMF ON EACH COIL- "HEALTHY" CONDITION
29
RECORD SUMMED OUTPUT FROM SEARCH COILS CONVERT TO FREQUENCY DOMAIN → A(f,t(n+1))
30
IS A(f,t(n+1)) >> A(f,t(n)) ?
NO
YES
31
RECORD SUMMED OUTPUT FROM SEARCH COILS CONVERT TO FREQUENCY DOMAIN → A(f,t(n+2))
32
IS A(f,t(n+2)) >> A(f,t(n))) ?
NO
YES
33
MEASURE AND RECORD RMS VALUE OF INDUCED EMF ON EACH COIL- "FAULTED" CONDITION
34
SUBTRACT EMF VALUE FOR "FAULTED" CONDITION FROM "HEALTHY" CONDITION FOR EACH COIL AND TAKE THE MODULUS
35
INPUT MODULI VALUES INTO FAULT LOCATION ALGORITHM & CALCULATE POSITION OF FAULT
36
DISPLAY INDICATOR OF FAULT OCCURRENCE AND POSITION OF FAULT WITHIN STATOR WINDING

FIG. 6

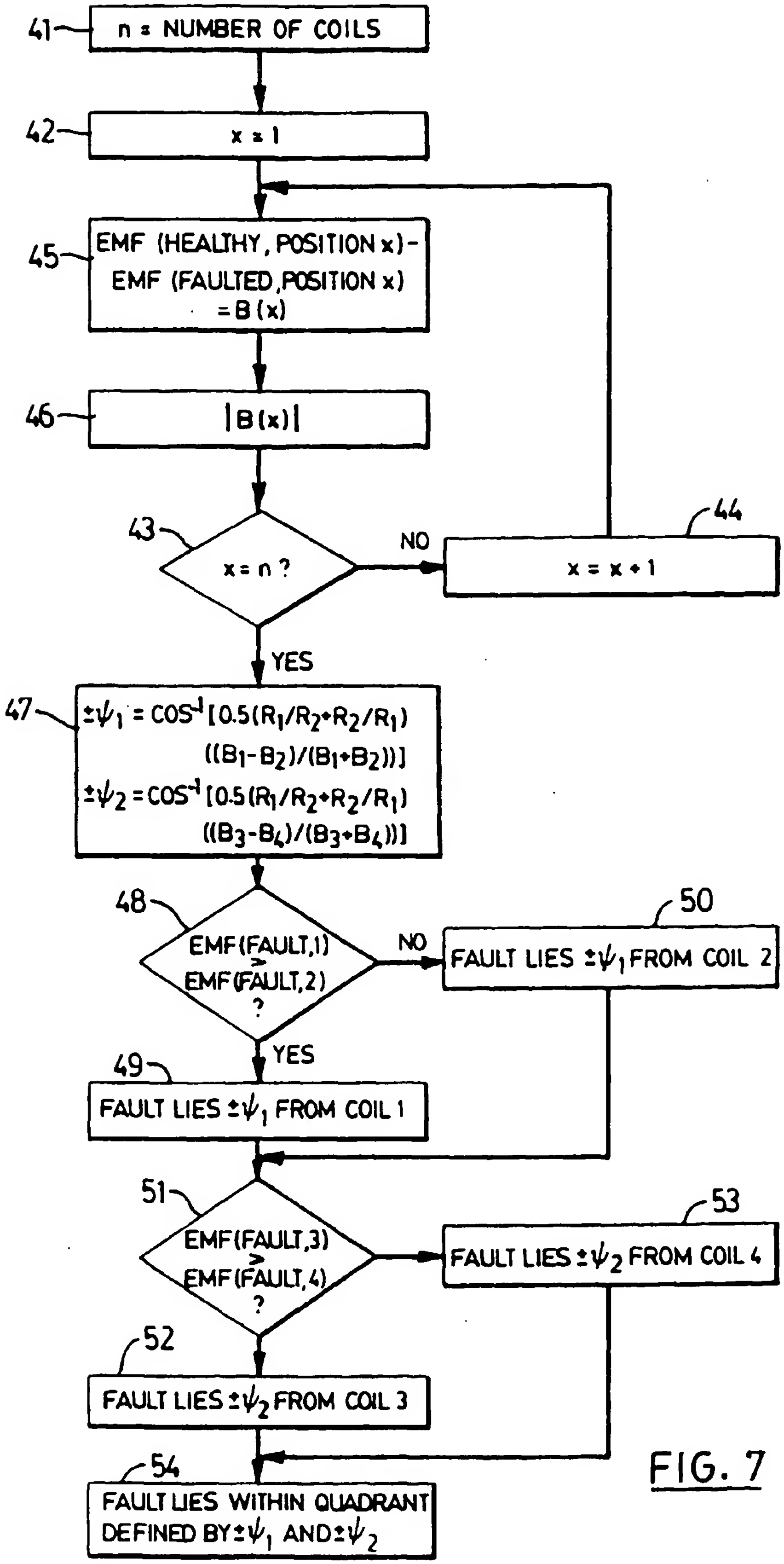

41
n = NUMBER OF COILS
42
x = 1
45
EMF (HEALTHY, POSITION x) - EMF (FAULTED, POSITION x) = B (x)
46
|B(x)|
43
x = n ?
NO
44
x = x + 1
YES
47
$\pm\psi_1 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)((B_1-B_2)/(B_1+B_2))]$
$\pm\psi_2 = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)((B_3-B_4)/(B_3+B_4))]$
48
EMF(FAULT,1) > EMF(FAULT,2) ?
NO
50
FAULT LIES $\pm\psi_1$ FROM COIL 2
YES
49
FAULT LIES $\pm\psi_1$ FROM COIL 1
51
EMF(FAULT,3) > EMF(FAULT,4) ?
53
FAULT LIES $\pm\psi_2$ FROM COIL 4
52
FAULT LIES $\pm\psi_2$ FROM COIL 3
54
FAULT LIES WITHIN QUADRANT DEFINED BY $\pm\psi_1$ AND $\pm\psi_2$

FIG. 7